

Finding the First Galaxies

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For astronomers who want to understand how the first galaxies formed in the universe, even the most distant galaxies that can be seen by the Hubble Space Telescope are not far enough.

Astronomers study distant galaxies by taking long exposures in deep survey fields. They choose fields that are empty of known sources, so that they are statistically representative of the Universe as a whole. Astronomers can compare the distribution of the detected galaxies in brightness, color, morphology and redshift to theoretical models, in order to puzzle out the processes of galaxy evolution.

In 2004, the Hubble Space Telescope was pointed at a small, deep-survey field in the southern constellation Fornax for more than 500 hours of exposure time. The resulting Hubble Ultra-Deep Field could see the faintest and most distant galaxies that the telescope is capable of viewing. These galaxies emitted their light less than 1 billion years after the Big Bang.

From the Ultra Deep Field and other galaxy surveys, astronomers have built up a history of star formation in the universe. The peak occurred about 7 billion years ago, about half the current age of the universe, when the number of stars that were forming was about 15 times the rate today.

As we go backward in time to when the very first stars and galaxies formed, the average star-formation rate should drop to zero. But when we look at the most distant galaxies in the Ultra-Deep Field, the star-formation rate is still higher than it is today. The faintest galaxies that Hubble can see are not the first galaxies that formed in the early universe. We haven't gotten there yet.

There are two reasons that the first galaxies are not seen in the Ultra-Deep Field: they are too faint for Hubble to see, and their light is redshifted into the infrared. To detect them, NASA is planning the James Webb Space Telescope for launch in 2013. Webb will have a 6.5-meter diameter primary mirror, much bigger than Hubble's 2.4-meter primary, and will be optimized for infrared observations to see the highly redshifted galaxies.

Building Galaxies

After the Big Bang, the universe was filled with primordial hydrogen and helium, expanding and cooling and responding to the gravity of growing clumps of dark matter. Theory says that large stars formed first, when the universe was about 100 million years old and rare hydrogen molecules could dissipate the energy of a cloud of gas, causing it to collapse. These large stars quickly exploded as supernovae, and the winds from the supernovae blew all the gas out of the relatively small dark matter clumps, disrupting any

chance of nearby neighbors. At about 250 million years after the Big Bang, theory says, hydrogen atoms began to radiate, breaking up the clouds of gas and forming stars much more rapidly, in a wide range of sizes. The first galaxies were born.

The first galaxies were small by today's standards, not much bigger than globular clusters. The early galaxies in the Ultra-Deep Field look like a mess: small, compact, blobby galaxies that resemble train wrecks. Their masses are hard to measure, but they are all clearly smaller than the Milky Way. We know that these galaxies evolved into the regular galaxies that make up the Hubble Sequence.

Galaxies build up through a process of hierarchical merging. We see galaxies that appear to be interacting gravitationally, producing tidal tails, rings, and other structures that indicate recent collisions. When two large spiral galaxies collide, in supercomputer simulations that trace the gravitational interactions of hundreds of millions of stars, they go through stages that look like the observed merging galaxies. The final result of these simulations is an elliptical galaxy. But when we leave a dark matter clump alone (in the computer simulation), it accretes the surrounding gas into a disk, which forms stars in a spiral pattern.

Spiral and elliptical galaxies are built up over cosmic history, as larger and larger galaxies merge. Spirals become ellipticals in major mergers; ellipticals merge together in the centers of galaxy clusters to become central dominant galaxies. By this process, the very small galaxies that first formed in the early universe were built up into the giant congregations we see today. Hundreds of small galaxies merged together to form a galaxy like our Milky Way. The observational implication of this is that the earliest galaxies are not only faint because they are very distant; they are also extra-faint because they were small.

The dark matter in a cluster of galaxies can act as a gravitational lens, focusing the light from background objects and boosting their observed brightness by a factor of 10 or more. Astronomers have used this to find a few faint and very distant galaxies, but the area that is magnified by each cluster is small, and it is hard to get a statistical sample.

The Ultra-Deep Field is a picture taken through 4 wide filters. For the distant galaxies, the ultraviolet part of the spectrum is redshifted through the filters. Light at wavelengths shorter than the first transition of Hydrogen, the Lyman alpha line, is absorbed by the gas between the galaxies, and the higher redshift galaxies successively drop out of the images made with the bluer filters. This is the way that astronomers measure the galaxies' redshifts. But at the highest redshifts, when the emitted ultraviolet appears only in the infrared part of the spectrum, Hubble can't see the galaxies at all, not even when using a gravitational lens.

Infrared light is heat radiation, so to see it with a telescope, the telescope has to be very cold. Otherwise, doing infrared astronomy with a warm telescope is like doing visible-light astronomy with a telescope full of light bulbs; the telescope itself outshines what you are looking at.

Heaters keep Hubble at room temperature, about 25 degrees Celsius, in order to maintain its stability as it goes in and out of sunlight in low Earth orbit. Although it has some infrared capability, the temperature of the telescope limits the sensitivity at the longest wavelengths. In 2003, NASA launched the Spitzer Space Telescope, an infrared-sensitive telescope which uses liquid Helium to stay colder than 262 degrees below 0 Celsius, or only 11 degrees above absolute zero. Spitzer provides the infrared sensitivity that Hubble lacks. When Spitzer was pointed at the Ultra Deep Field, astronomers were surprised to discover that some of the most distant galaxies seen were shining brightly in the infrared.

When galaxies first form stars, their light is dominated by their largest stars. These stars, 30 to 50 times the mass of our Sun, are very hot and put out most of their radiation in the ultraviolet. While they live, they outshine all of the smaller stars in the galaxy. But burning brightly has its price, and the most massive stars are also the shortest lived. After just a few million years, they run out of hydrogen fuel in their cores and quickly end their lives in a supernova. Smaller stars, like our Sun, come to dominate the light output of the galaxy. These smaller stars are cooler and put out most of their energy as visible or near-infrared light, with much less ultraviolet.

In the distant galaxies of the Ultra Deep Field, observed just 1 billion years after the Big Bang, their emitted ultraviolet light is redshifted to the edge of the visible light band, and their emitted visible light is redshifted into the infrared. The Spitzer Space Telescope detections showed that these galaxies were not forming their first generation of stars, but contained a substantial population of older stars, possibly as much as 400 or 500 million years old. When these galaxies were first formed, the universe was much less than 1 billion years old, and their ultraviolet light was redshifted well into the infrared, beyond the reach of Hubble's cameras.

Although Spitzer is cold enough to detect light in the infrared, it is smaller than Hubble. Hubble's primary mirror is 2.4 meters in diameter; Spitzer's is only 85 centimeters. This limits Spitzer's sensitivity to faint galaxies in two ways. First, it is simply not collecting enough light to see galaxies fainter than those in the Ultra Deep Field. Second, the resolution of a telescope in space depends on ratio of the wavelength of light divided by the diameter of the primary mirror. With longer wavelengths and a smaller mirror, Spitzer cannot take as sharp pictures as Hubble and the faintest galaxies in its images overlap each other.

Webb

The James Webb Space Telescope will be colder than Hubble and larger than Spitzer. Sitting behind a giant sunshield, the telescope will radiate its heat to deep space and passively cool to more than 225 degrees below zero Celsius, or 50 degrees above absolute zero. Its large mirror and cold temperature translates into the infrared sensitivity needed to detect the first galaxies that formed about 400 million years after the Big Bang.

There are major technological challenges in building the Webb observatory. Hubble is in low-Earth orbit, about 375 miles above the Earth. It orbits Earth once every 90 minutes, going in and out of the sunlight in each orbit. For stability, the telescope is kept at a

constant temperature using heaters. Spitzer was launched into a solar drift-away orbit, orbiting the Sun behind Earth and drifting 10 million miles from Earth each year. By getting away from Earth, Spitzer is able to use a shield to block the sunlight from heating the telescope.

Webb will also hide behind a sunshield, one as big as a regulation tennis court. It will be launched into a special orbit around the second Lagrange point in the Earth-Sun system, called L2, about 1 million miles from Earth. More distant from the Sun than Earth, the observatory would normally take longer than one year to orbit the Sun, and slowly drift away, like Spitzer. However, at L2, Earth's gravity will pull on Webb just enough to keep it in synch and the Sun, Earth, and the L2 point are always in a line. Webb's sunshield will not only protect the telescope from the Sun's heat, but also from scattered light from the sunlit parts of the Earth and Moon. The telescope will always be overhead at midnight each night.

The largest rockets are 5 meters in diameter, so another technology development needed to enable the 6.5 meter diameter Webb is to deploy the mirror in space. The primary mirror is made up of 18 segments, each with independently controllable position. The mirror will stand on its edge in the rocket and the three segments on each side will be folded back like the leaves of a table top. The sunshield is folded around the mirror. After launch, several items will be deployed. The solar panels will unfold to supply the observatory with power. The communications antenna will point toward Earth, and a deployed isolation tower will separate the telescope from the spacecraft. The sunshield will then unfold, and its five layers will separate.

The reason the sunshield has five layers is both so that heat can escape between the layers, but also so that if it is punctured by a micrometeorite, the holes will be unlikely to line up in such a way that sunlight will scatter onto the primary mirror. Finally, the secondary mirror will be supported on a three-legged spider, and the leaves of the primary mirror will be folded out. Once everything has been deployed on the observatory, the telescope will be pointed at a bright star, and the 18 petals of the primary mirror will be brought to a common focus.

All this new technology comes at a price. The total lifecycle cost of Webb will be about \$5 billion for NASA, plus the additional contributions from Europe and Canada. Earlier estimates, in the late 1990s, ranged from \$500M to \$1B for construction costs only, which did not include technology development, design work, or post-launch operations. But even the cost of the construction phase has more than doubled. Much of this is due to the rigorous testing program that will ensure that Webb will work when it gets into space. The current cost of Webb is comparable to the cost of Hubble's construction, once corrected for inflation and changes in accounting procedures. Following an independent review, the Webb project recently transitioned to its formal "implementation" phase, and NASA certified the budget and schedule to Congress.

A General-Purpose Observatory

When it's launched, the James Webb Space Telescope will be the successor to the Hubble and Spitzer Space Telescopes. Like Hubble, it is a major international collaboration, with contributions from the European and Canadian Space Agencies. Although initially designed to detect the first galaxies that formed in the early universe, it will be a general-purpose observatory able to address nearly every aspect of astronomy.

Stars and planets form in dense clouds of gas and dust in a complex interaction between gravity, momentum, gas pressure and magnetic fields. The dust blocks much of the ultraviolet and visible light from escaping the cloud, and stellar cradles such as M16 appear as beautiful, but opaque nebulae. Infrared light penetrates the dust to reveal the forming stars. At a later stage, the star forms a proto-planetary debris disk; the star heats the disk so that it glows in the infrared. By providing high-resolution sensitive images in the infrared, Webb will be a powerful tool for investigating the formation of stars and their planetary systems in the Milky Way.

Like Hubble and Spitzer, it will be used by thousands of astronomers from around the world, and will deliver beautiful pictures of the sky. And like Hubble and Spitzer, its most important discoveries are likely to be of things we haven't even thought of yet.

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Possible pictures:

- The Hubble Ultra Deep Field, either all of it or a close-up of a subsection. The UDF could also be the background for the first two pages of the article.
- Perhaps a close-up showing faint red distant galaxies in the UDF, with both Hubble and Spitzer data (note: these are basically point sources, so they aren't all that exciting visually.)
- A picture of a merging galaxy pair, such as The Mice.
- Graph showing the history of star formation (density) in the Universe, and indicating that the point at 1 Gyr after the Big Bang is still higher than the current value.
- A model spectrum of an old galaxy compared to a young galaxy along with the HST/Spitzer points of an old galaxy at $z=6$.
- A picture of JWST, perhaps a size comparison with Hubble and Spitzer.
- A graphic showing the L2 orbit.

A graphic showing the deployment sequence.